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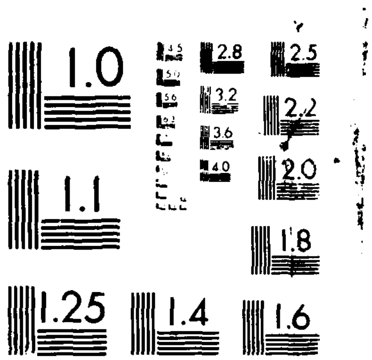

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Series of Tests

William R. Uttal

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This is the final report of a research program that explored the perception of visual forms. The project consisted of psychophysical studies in which stereoscopically generated, three-dimensional forms were studied in terms of their detectability, discriminability, recognizability, and reconstructability. The project produced a book and 11 articles, all of which spoke to the problem of how humans see forms in space. Two more articles are in progress. This report summarizes the findings of the extensive series of experiments carried out during the program.

Results of this study are applicable to a wide range of U.S. Navy interests including computer vision, autonomous vehicles, remotely controlled devices (teleoperators), and displays.

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SUMMARY

This is the final report of a research program that explored the perception of visual forms. The project consisted of a series of psychophysical studies in which stereoscopically generated, three-dimensional forms were studied in terms of their detectability, discriminability, recognizability, and reconstructability. The project produced a book and 11 articles, all of which spoke to the problem of how humans see forms in space. Two other articles are in progress. This report summarizes the findings of the extensive series of experiments carried out during this program.

The results of this study are applicable to a wide range of U.S. Navy interests including computer vision, autonomous vehicles, remotely controlled devices (teleoperators), and displays.

CONTENTS

CONCLUSIONS FROM STUDIES

How do we see forms? That is the question that has guided and motivated my research for almost 15 years. Nevertheless, it is a question so encompassing and vague it cannot be attacked empirically when stated baldly. To make any progress, this complex problem must be simplified so its more specific corollaries become amenable to experimental manipulation. We must simplify the real world so that it becomes tractable to *controlled manipulation* and *computational simulation*—the best experimental and theoretical tools currently available to us in this interdisciplinary field of visual form perception. This is the fundamental method of science—the search for understanding of complex systems by examination of the nature of their constituent simple components. The most important long-range outcome of the emergence of this strategy of attempting to understand the complex natural world by analyzing it into its parts, it can be fairly argued, has been nothing less than the replacement of speculation by experimentation and of opinion by testable proof.

In the spirit of the method of detail, we were led in this present work to study the specifics of form *detection*, *discrimination*, or *recognition* rather than the much more global and much less well defined concept called form *perception*. In brief, the goal of this study was to determine the influence of the real or apparent properties of stereoscopically generated, three-dimensional forms on our ability to detect, discriminate, and recognize. We did so both by carrying out simplified psychophysical experiments and by testing analytic models of the forthcoming results.

In an analogous way, the full richness of the pictorial scenes that impinge upon our visual receptors is simply too complicated for the scenes themselves to be used as the eliciting stimuli to explicate the microscopic details of how we see forms. Thus, in another great, but much more modern, tradition of psychological science we simplify and abstract scenes down to flashes or lines or dots that only partially represent the full complexity of pictorial reality to carry out an understandable and controllable experiment.

These two great simplifications—the method of detail and, in one observer's words, "the graceful relaxation of stimuli"—are the bases of the work described in this final report just as they were the guides for the studies described in its three predecessors (Uttal, 1975; 1983; 1985). The former was the reason for the use of the highly structured and simplified psychophysical procedures to be described. The latter is the reason that dotted abstractions of visual reality are used as stimuli. We can say without too much exaggeration that the use of both strategies largely explains why considerable progress has been made in what otherwise is often a confounded and tangled research area.

There are some caveats that should be explicitly stated at the outset. I cannot overemphasize my belief that the processes assayed by the kind of experiment reported here are characteristic of only a very narrowly defined level of vision. As many other students of the field have suggested, and as I tried to make clear elsewhere (Uttal, 1981), any visual perceptual experience is affected by many different levels of information processing starting with the absorption of light—the physical stimulus—by photo receptors in the retina and continuing with the cognitive manipulation of the conscious percept.

I believe that the abstractions of physical reality—the dotted stimulus form and the highly formalized experimental paradigm, a forced choice response to a nonrandom dotted form hidden in a random dot mask—chosen as the experimental vehicles in the present study determine that most of the results obtained reflect the properties of an intermediate level of visual processing. This level is well beyond the processes best analyzed in terms of the chemistry and physics of the receptors but, in the main, is not as high as the levels characterized as cognitive or attentive. This level is largely passive and automatic and occurs without effortful attention to the local details of the stimulus. The conclusions to be drawn, therefore, speak mainly to this intermediate processing level. My warning is

that it would be theoretically treacherous to overgeneralize them to other domains within which we already know that different rules apply.

Another caveat should be expressed concerning the use of three-dimensional, stereoscopic material as stimulus forms in this study. While we have found these forms extremely useful to study a kind of form perception that is not often an object of research attention, *the genesis of the stereoscopic depth experience itself is not the problem of interest here*. The emergence of stereodepth from the invariances extracted from disparity cues by computational and neural mechanisms is a process that is beginning to be understood. Indeed, in this present work the ability to generate depth from disparity is taken as a given. Rather, *the perceptual manipulation of the perceived forms exhibiting that apparent depth generated subsequent to the solution of the correspondence and interpretation problems was the research target of interest in this study*. By the correspondence problem I refer to the surprisingly difficult task, particularly in a random dot stereogram, of determining which dots in one eye's view are associated or correspond to which dots in the other eye's view. Without solving this problem, of course, the disparity between each pair of "corresponding" points could not be evaluated and an experience of apparent depth could not be generated.

By the interpretation problem, I am referring to the task of determining what shape or form is specified by the aggregate disparities of all pairs of dots in the stimulus scene. Neither of these tasks is explored here nor are any of the conditions that might affect them manipulated in this study. We assume that the observers in our experiments solve these problems, but that they do so under controlled conditions that do not affect the solutions of the quite different tasks towards which our experiments are directed.

Though this fine distinction may seem to be a bit of verbal nit-picking, the empirical tasks (i.e., experimental procedures) used in this study actually distinguish between these two sets of processes—correspondence and interpretation on the one hand and detection, discrimination, and recognition on the other—in a subtle way. In the first case, disparity cues always produce a strong experience of depth in our experiments: the correspondence and interpretation tasks are, in other words, always solved before the experiment commences. On the other hand, the strong induced experience of stereodepth often does not produce a measurable influence on some task in which the observer is asked to manipulate or process another aspect of that apparent depth. This distinction is important because it is tantamount to the specification of an even finer taxonomy of the visual processes hitherto proposed. Some very closely related processes that may be sometimes difficult to verbally disentangle turn out to be vastly different in their response properties.

The point I emphasize here is that the properties of the *apparent* surfaces are the problems of interest in this study, not the means by which the disparate images are brought into *correspondence* or how this disparity information is *interpreted* as objects in depth.

If the process of generating the stereoscopic depth experience is, at best, only of secondary interest in this context of the present study, a visual process of primary interest is the emergence of global form from discrete samples. How do we reconstruct the form when it is only partially presented by a constellation of dots? How is it that we see what are virtually complete "subjective surfaces" in three dimensions when the stimuli are composed of broadly spaced, discretely sampled, dots? The problem of reconstruction from samples has currently become one of the main foci of attention in my work. However, that potential work on reconstruction, which is closely related to the interpretation problem, must also be distinguished from the other problems of more immediate interest in the present context—the detection, discrimination, and recognition of the reconstructed forms.

The vehicle for this research project is, as noted above, the dotted form—a "gracefully relaxed" abstraction of real visual scenes that is both computationally and psychophysically tractable.

By psychophysically tractable, I refer to the ability of the stimulus material to serve in a wide variety of different visual tasks and to be manipulable at the preattentive level of processing at which I believe the perceptual transformations we are studying mainly lie. Ideally, the experiments carried out should be only minimally confounded by receptor or cognitive level effects that are extraneous to this intermediate level of visual form perception. By computationally tractable I refer to the fact that the stimulus-forms must also be simple enough to be amenable to formal mathematical or computer analysis and modeling. Arrays of dots, discrete samples of continuous forms, meet this criterion whereas the much more complex and all-too-complete photograph, i.e., images of a real world scene, usually does not. A modern graphics computer is capable of processing a 64- or 100-dot pattern in three dimensions in a few seconds or minutes, whereas it would bog down hopelessly in a computational explosion should the billion or so pixels of a three-dimensional volume (a thoroughly plausible possibility considering that volumes can be sampled as densely as is the currently standard 1000- by 1000-pixel graphics display image and be a thousand locations deep as well) be submitted to it for processing.

Dotted images have many other advantages. The visibility (in the broadest sense of the term) of the forms the dots are sampling can be continuously regulated by embedding an ordered, dotted form in an array of randomly distributed dots. This provides a means of degrading a stimulus in a precise manner so the powerful information processing ability of the visual system can be challenged. In fact in many less demanding signal-to-noise situations, the visual system performs so well and is so adaptive it is difficult to tease out any differential effects of form, per se.

A related advantage of the masked, dotted forms used here is that, like the random dot stereograms of which they are a subset that were introduced into visual research by Julesz (1960), they reduce extraneous (i.e., irrelevant to the purposes of the experiment) cues to a minimum and allow the study of a pure form of visual perception unconfounded by redundant cues that would "give away" the game without challenging the visual task of interest. In other words, dotted stimulus-forms reduce the number of redundant cues to a minimum, if not to a single one (arrangement?), and allow us to test what we intend to test rather than inadvertently providing a multicue stimulus-scene to the ever opportunistic, powerful, and multiply-sensitive visual system.

Another important attribute of dotted forms is that because the *organization* of the "trivial" constituent dots is everything as far as the perceiver is concerned, they allow the experimenter to specifically explore the effect of overall arrangement and global form and to minimize the influence of local features. There are, in fact, no local "features" in a dotted form, only the minimum amount of information necessary to define the location of the dot—all else is nothing more than a manifestation of the organization and spatial interrelationships between the dots. Since the human visual system, as the Gestaltists would have taught us if we had been listening, sees more by virtue of the *arrangement of the parts* and less by means of the *nature of the parts,* this seems to me to be a particularly appropriate means of exploring global form perception.

Another important advantage of dotted forms, particularly in the present context in which we wish to compare performance in a number of different tasks, is that virtually the same stimulus materials—the to-be-perceived forms and the interfering masks—can be used unchanged in each of the experimental conditions without contamination by experience or memory. Indeed, we can make comparisons between detection (is there anything there?), discrimination (are those two things the same or different?), and recognition (what is the name of that thing?) using only slightly different methodologies and apparatuses, the same stimuli, and, as we shall see, even in some instances the same observers. Because the stimuli are degraded in exactly the same way—the signal-to-noise ratio is varied by adding greater or lesser numbers of randomly positioned noise dots—direct comparisons can be made between relative performance levels and qualitative sensitivities in each of the three tasks.

In the past our work on masked, dotted form perception has primarily been concerned with detection, first of two-dimensional stimulus-forms (Uttal, 1975), then of planar surfaces in three-dimensional space (Uttal, 1983), and then of nonplanar surfaces in three-dimensional space (Uttal, 1985). A few rules of visual perception emerged in this work that characterized particular situations. I will summarize these rules later, but the important point to be reiterated here is that the rules observed in one context often did not generalize to other, at first glance analogous, experimental conditions in spite of the unusually good control to which I just alluded. This is the message of the metarule presented earlier. What held true in two dimensions does not necessarily hold in three dimensions and what held for regular forms does not always hold for random forms. As I have already noted, specificity of process, rather than generality, was the rule of rules. In some cases the discrepancy between conditions was not only surprising, but downright astonishing, and certainly counterintuitive.

Specifically, two rules emerged from our earlier studies that, from some points of view, must have seemed to be inconsistent with each other. Yet each was so well founded empirically they could not be dismissed as artifactual or the superficial outcome of differing procedures or individual differences. These rules are as follows:

1. The rule of linear periodicity. This rule emerged from the two-dimensional work (Uttal, 1975). It summarized much of the detection work carried out in that domain by asserting that evenly spaced (periodic, in our terminology) straight lines of dots were the prepotent stimulus for two-dimensional detection. This rule was predicted and, to a certain degree, even explained by a two-dimensional autocorrelation transformation (Uttal, 1975).

2. The rule of three-dimensional noncomputability. This rule reflected the empirical fact that there was little or no effect of the three-dimensional form on nonplanar stimulus detectability. Even though form in two dimensions had been a powerful determinant of detectability, our observers seemed to be insensitive to the three-dimensional shape (i.e., the depth parameters) of the stimulus. This was so in spite of the fact that the solid *appearance* of the stimulus-forms was striking when they were viewed through the stereoscope. Unlike the first rule, this phenomenon remains to this time theoretically unexplained, but is often idiosyncratic and violated in what are only slightly different experimental paradigms involving alternative tasks.

Measures of form effects were always the most inconsistent and labile outcome of our experiments. Interobserver differences were the greatest when data were analyzed for this variable. The number of different stimulus-forms in the experimental set, the experimental tasks, and many other variables of an experiment seemed to produce wide variation in answers to the question—what is the effect of stimulus-form on detection, discrimination, and recognition? Indeed, at present, we cannot answer this question with any degree of conviction.

Only when a different kind of analysis—error matrices—was introduced (i.e., other than plotting our raw percentage-correct scores as a function of form) did stable effects of form emerge; these matrices showed relatively reliable and stable confusions, and although this was an unexpected kind of differential performance as a function of form, the question we sought to answer originally, it was a form effect. Possibly in some way we do not understand yet, the use of a set of different forms taps into processes that are more active or cognitive than they are passive and preattentive.

Clearly we found during the course of this study that the perceptual universe assayed by this dotted stimulus-form-in-dotted-noise experimental paradigm and the visual processes being invoked are much more complex and the forthcoming results are much less generalizable than initially suggested. The issue of a unified theory as opposed to a "grab bag of perceptual tricks" remains persistent and perplexing in even this little corner of perceptual psychophysics. But this is not the only controversial

problem attacked in this study. Another persistent problem at this intermediate, postreceptor, but preattentive level of visual perception concerns whether the detection, discrimination, recognition, and any other related visual processes yet to be encountered operate in parallel (concurrently) or in serial (sequentially). This is an issue that has attracted widespread attention in recent years, particularly as the concept of parallel processing evolved in both computer science and in neuroscience.

An alternative conceptual solution to the question of serial versus parallel organization deals with vision as a series of sequential stages or levels of information processing within which successively more complex transformations and decisions are made and at which progressively more information is required. One intuitively attractive hypothesis of this genre relevant to the present study is that the human observer first *detects* forms on the basis of a minimum amount of information, then is able to *discriminate* two detected stimuli from each other as slightly more information becomes available, and subsequently *recognizes* or identifies the stimulus-form when additional amounts of information are available.

As noted, a major purpose of the present study is to explore the effect of three-dimensional form on detection, discrimination, and recognition. In some of our earlier work (Uttal, 1985), as summarized by the rule of three-dimensional noncomputability, we observed that the stereoscopically generated, three-dimensional geometry of a stimulus-form did not affect its detectability. This result suggests that even though the human visual system is capable of easily perceiving three-dimensional form (specifically depth) it is not necessarily capable of coping with the enormous information processing requirements of all kinds of three-dimensional perceptual processes.

These studies also added comparisons of the discriminability and recognizability of regular and random forms to the comparable results for detection. Unfortunately, the results for similar experiments in detection have been equivocal, and I do not now believe that my earlier finding—randomly sampled stimuli are detected better than regularly sampled stimuli—is valid. In spite of the fact that this type of experiment is known to be confounded—there is a monocularly visible straight line cue present in the regular stimuli—to determine how our observers deal with this variable is still worthwhile. However, the advantage given to the regular stimuli by the additional monocularly perceived straight lines of dots makes independent evaluation of the influence of this variable impossible.

Finally, a theoretical goal of this work was to present a mathematical model of the perceptual performance of our observers in the three tasks. The development of the integrated model of visual form perception is now well underway, and a follow-up report is being prepared.

Another report in progress deals with a modest digression—an examination of face perception in which we specifically set out to compare the influence of global and local cues to the detection, discrimination, and recognition of faces.

SUMMARIES OF RESEARCH PUBLICATIONS

1. Uttal, W.R. (1987) "The psychobiology of mind." In G. Adelman, (Ed.) *The Encyclopedia of Neuroscience* (pp. 672-674.) Boston, MA.: Birkhauser.

This encyclopedia article dealt with the relationship between mental processes and neurophysiological results. The view was expressed that great caution had to be maintained in drawing putative associations between these two domains, but that there was without question a direct and unique relationship between the two.

2. Yu, B., Brogan, J., Robertson, S., and Uttal, W.R. (1985) "The detection of Chinese strokes and characters in visual noise." *Perception & Psychophysics, 38* , 23-29.

This report discussed the effects of experience, method, and stimulus form on the detectability of dotted approximations to Chinese strokes and characters when they are masked by random-dot visual noise. The results of two experiments are interpreted to show that experience effects are non-existent or small. Furthermore, even when small effects are present, they are in the direction opposite to that predicted. Similarly, method plays only a minor role in determining performance. However, strong stimulus-form effects exist that are well predicted by a previously developed autocorrelation-like computational model of the dotted form detection process.

3. Uttal, W.R. (1985) "An analytic success: A synthetic bust." (Review of Geissler, Buffart, Leeuwenberg, and Sarris (Eds.) (1985) *Modern Issues in Perception.) Contemporary Psychology. 30*, 705-706.

4. Kincaid, W.M. and Uttal, W.R. (1986) "The effect of 3-D orientation and stretches on the detection of dotted planes." *Perception & Psychophysics, 39*, 392-296.

This experiment used a procedure in which a dotted stimulus form was masked by random dots to explore human form detection. The dotted stimulus forms were located in a stereoscopically generated three-dimensional rectangular volume. The form was defined by a set of randomly positioned dots always restricted to a plane. The orientation of the dotted plane varied from fronto-parallel to diagonal around a vertical axis of rotation passing through the center of the rectangular volume. The plane always stretched across the region from sidewall to sidewall. Since the volume was deeper than it was wide, both the apparent area and the apparent dot density varied with orientation. The masking dots were distributed at random throughout this volume. For a constant number of stimulus-form and masking dots, however, the detectability of the plane was shown not to depend upon orientation. This counterintuitive result, in conjunction with earlier findings, suggest that there is a range of conditions over which detectability depends only upon the total numbers of stimulus and masking dots and not upon subjective orientation, density, or area of the plane. Therefore, observers respond as if they were sensitive to the retinal two-dimensional density rather than the apparent three-dimensional density.

5. Uttal, W. R. (1987) "Misdirection in psychobiology (Review of Gilinsky's (1984) Mind and Brain)" *Contemporary Psychology, 31*, 977-988.

6. Uttal, W. R. (1986) "Computers in vision research: Introduction." *Behavior Research Methods, Instruments and Computers,18*, 484-486.

This article was the introduction to a special issue of this journal on the use of computers in vision research. Uttal was editor of the special issue.

7. Uttal, W.R. (1987) *The Perception of Dotted Forms*. Hillsdale, N.J.: Erlbaum

The findings reported in the monograph can be summarized as follows:

A. Detection, discrimination and. recognition appea. to be generally organized into a hierarchy in which successively higher amounts of information are required to overcome the degrading effects of masking random noise dots.

B. In a few exceptional conditions, typicall, at high masking dot densities, discrimination sometimes occurs at lower signal-to-noise ratios than detection.

C. Detection and discrimination performanc. both appear to be relatively uninfluenced by the shape of the surface in terms of their raw scores. Recognition scores are idiosyncratically influenced by stimulus shape varying with observer groups and stimulus set. Both discrimination and recognition, however, do show a very reliable sensitivity to form in the error matrices for the various combinations that must be discriminated or the confusion errors in the recognition task.

D. The errors of discrimination and of recognition indicated in the error matrices are strongly diagonally symmetrical, indicating that no significant response bias occurs and that the responses are largely stimulus driven.

E. Detection, discrimination, and recognition data both show a prepotency of the regularly sampled forms over the randomly sampled one. When the standard set of eight stimulus-forms are presented intermixed, replications of earlier experiments show that the rule of random sampling (in which single random forms appeared to be detected better than regular ones) was incorrect.

F. In the discrimination experiment with random stimuli, certain confusions (i.e., poor discriminations) occurred. The strongest ones are as follows:

(1) The cylinder was difficult to discriminate from the arch and the saddle.

(2) The hemisphere and the paraboloid of rotation could not easily be discriminated from each other, but were quite discriminable from all others.

(3) The two-dimensional cubic was difficult to discriminate from the one-dimensional cubic and the plane, but the one-dimensional cubic was easily discriminated from the plan.

G. In the recognition experiment, using random stimuli, the pattern of results was virtually identical to the strongest confusions in the discrimination experiment, but the differences between the first and second tier of error scores were greater in recognition than in discrimination.

(1) The cylinder, arch, and saddle were confused with each other.

(2) The hemisphere and paraboloid were confused with each other.

(3) The 1-D cubic and the 2-D cubic were frequently confused, and the 2-D cubic (but not the 1-D cubic) was confused with the plane.

H. When an elastic plane is rotated to different positions in a rectangular space, it does not vary in detectability in spite of the fact that there is a greater than two-to-one variation in its apparent dot density. This result negates any possibility that local region effects can account for the null effect of stimulus-form in the raw percent-correct graphs.

8. Uttal, W.R., Davis, N.S., Welke, C, and Kakarala, R. (1988)
"The reconstruction of static visual forms from sparse dotted samples."
Perception & Psychophysics. (In press)

This study explored the ability of observers to perceptually reconstruct very sparsely sampled, stereoscopic, dotted surfaces. The observer's performance exceeds that of a simple surface fitting algorithm that serves as a first approximation model to the solution of the perceptual problem. We explored various attributes of the stimulus-surfaces, but were unable to find any single one that could account for the measured performance. Therefore, we propose that the observer jointly uses several surface attributes, all of which are global, to distinguish one form from another. Collectively, these attributes define what is meant by form in this study. We suggest that our results argue for a globally precedent, multidimensional model of form reconstruction as opposed to a local feature, unidimensional interpretation.

9. Uttal, W. R., Davis, N. S., and Welke, C.
"Stereoscopic perception with brief exposures." (Submitted)

This report describes the results of an experiment in which it is demonstrated that a powerful and compelling stereoscopic experience is elicited with very brief (<1 msec) stimulus durations. Observers are able to recorgnize briefly flashed stereoscopic random dot surfaces in the absence of monocular contours with a high degree of success. The results are shown to be closely related to the range of depths in any stimulus-form. Previous reports of a temporal threshold for stereopsis seem to be associated with inadequate fixation cues and incomplete dichoptic image registration.

10. Uttal, W. R. "On the meaning of models of visual processes."
(Submitted)

This article highlights a number of arguments that suggest that computational models of visual processes and their attendant neurophysiological corollaries may be subject to certain constraints and limits. The arguments are drawn from a number of fields—mathematics, automata theory, chaos theory, thermodynamics, neurophysiology, and psychology. Collectively, these arguments suggest that computational models are untestable and unverifiable with regard to their instantiations in the nervous system regardless of how good a fit there is between the performance of the model and the cognitive process being considered. It is argued, therefore, that computational models may be good descriptions of perceptual and other cognitive processes, but they cannot be reductive explanations in the sense expected by many workers in this field. This argument is presented in an effort to clarify the appropriate meaning of these models, not to dissuade workers from forging ahead in the modeling endeavor that is acknowledgedly converging on a increasingly accurate appreciation of the nature of visual processes.

ARTICLES IN PROGRESS

11. Uttal, W. R. and Bradshaw, G. "An integrated computational model of human perceptual-motor performance."

This article presents a computational model of a broad range of human form perception processes, including the responses acts of locomotion to a designated target. It consists of algorithms that perceive objects, define a three-dimensional world model, and plans a path from the current location of the perceiver to the location of the objects in a turbulent and perturbing world.

12. Uttal, W. R. and Welke, C. "The perception of faces."

This article reports on some experimental work considering the detection, discrimination, and recognition of human faces in which it is shown that both local and global properties are important in perception.

STAFF

Persons who have participated in this project since it moved from the University of Michigan in May 1975 are

a. Visiting colleagues

Gary Bradshaw, Professor at the University of Colorado

b. Graduate students

Ramakrishna Kakarala, University of Michigan

Kurt Skifsted, University of Michigan

c. Research assistants

Sharon Atkins

Wendy Dorko

Cynthia Welke

Nancy Davis.

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Dr. Earl Alluisi
Office of the Deputy Under Secretary of Defense
OUSDRE (E&LS)
Pentagon, Room 3D129
Washington, DC 20301

DEPARTMENT OF THE NAVY

Aerospace Psychology Department
Naval Aerospace Medical Research Laboratory
Pensacola, FL 32508

Aircrew Systems Branch
Systems Engineering Test Directorate
U.S. Naval Test Center
Patuxent River, MD 20670

Mr. Phillip Andrews
Naval Sea Systems Command
NAVSEA 61R2
Washington, DC 20362-5101

LCDR R. Carter
Office of Chief on Naval Operations
OP-933D3
Washington, DC 20350

Dr. L. Chmura
Computer Sciences & Systems
Code 5592
Naval Research Laboratory
Washington, DC 20375-5000

Dr. Stanley Collyer
Office of Naval Technology
Code 222
800 North Quincy Street
Arlington, VA 22217-5000

Commander
Naval Air Systems Command
Crew Station Design
NAVAIR 5313
Washinton, DC 20361-0001

Dean of the Academic Departments
U.S. Naval Academy
Annapolis, MD 21402

Director
Technical Information Division
Code 2627
Naval Research Laboratory
Washington, DC 20375-5000

Dr. Robert A. Fleming
Human Factors Support Group
Naval Personnel Research and Development Center
1411 *South Fern Street*
Arlington, VA 22202-2896

Mr. Jeff Grossman
Human Factors Laboratory
Code 71
Navy Personnel R&D Center
San Diego, CA 92152-6800

Mr. Paul Heckman
Naval Ocean Systems Center
San Diego, CA 92152-5000

Human Factors Branch
Code 3152
Naval Weapons Center
China Lake, CA 93555

Human Factors Department
Code N-71
Naval Training Systems Center
Orlando, FL 32813

Human Factors Engineering
Code 441
Naval Ocean Systems Center
San Diego, CA 92152-5000

CAPT Thomas Jones
Code 125
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Mr. Todd Jones
Naval Air Systems Command
Code APC-2050
Washington, DC 20361-1205

Dr. Michael Letsky
Office of the Chief of Naval Operations
(OP-01B7)
Washington, DC 20350

LT Dennis McBride
Human Factors Branch
Pacific Missile Test Center
Point Mugu, CA 93042

LCDR Thomas Mitchell
Code 55
Naval Postgraduate School
Monterey, CA 93940

Dr. George Moeller
Human Factors Department
Naval Submarine Medical Research Laboratory
Naval Submarine Base
Groton, CT 06340-5900

CAPT W. Moroney
Naval Air Development Center
Code 602
Warminster, PA 18974

Dr. A. F. Norcio
Computer Sciences & Systems
Code 5592
Naval Research Laboratory
Washington, DC 20375-5000

CDR James Offutt
Office of the Secretary of Defense
Strategic Defense Initiative Organization
Washington, DC 20301-5000

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LCDR T. Singer
Human Factors Engineering Division
Naval Air Development Center
Warminster, PA 18974

Dr. A. L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps
Washington, DC 20380

Mr. James Smith
Code 121
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Special Assistant for Marine Corps Matters
Code OOMC
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Mr. H. R. Talkington
Deputy Technical Director
Code 02
Naval Ocean Systems Center
San Diego, CA 92152-5000

Dr. Saul Luria
Naval Submarine Medical Research Laboratory
Naval Submarine Base
Groton, CT 06340-5900

DEPARTMENT OF THE ARMY

Director, Organizations and Systems Research Laboratory
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Dr. Michael Drillings
Basic Research Office
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Dr. Edgar M. Johnson
Technical Director
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Technical Director
U.S. Army Human Engineering Laboratory
Aberdeen Proving Ground, MD 21005

DEPARTMENT OF THE AIR FORCE

Dr. A. D. Baddeley
Director, Applied Psychology Unit
Medical Research Council
15 Chaucer Road
Cambridge, CB2 2EF England

Dr. Kenneth R. Boff
AF AMRL/HE
Wright-Patterson AFB, OH 45433

Dr. A. Fregly
Life Science Directorate, AFOSR
Bolling AFB, Bldg 410
Washington, DC 20332-6448

Dr. J. Tangney
Life Sciences Directorate, AFSOR
Bolling AFB, Bldg 410
Washington, DC 20332-6448

OTHER GOVERNMENT AGENCIES

Defense Technical Information Center
Cameron Station, Bldg 5
Alexandria, VA 22314 (12 copies)

Dr. Clinton Kelly
Defense Advanced Research Projects Agency
1400 Wilson Blvd
Arlington, VA 22209

Dr. Alan Leshner
Division of Behavioral and Neural Sciences
National Science Foundation
1800 G. Street, N.W.
Washington, DC 20550

Dr. M. C. Montemerlo
Information Sciences and Human Factors
Code RC, NASA Hdqtrs
Washington, DC 20546

OTHER ORGANIZATIONS

Dr. Jesse Orlansky
Institute for Defense Analyses
1801 N. Beauregard Street
Alexandria, VA 22311

Dr. Richard Pew
Bolt Beranek & Newman, Inc.
10 Moulton Street
Cambridge, MA 02238

Dr. Tomaso Poggio
Massachusetts Institute of Technology
Center for Biological Information Processing
Cambridge, MA 02139

Dr. Whitman Richards
Massachusetts Institute of Technology
Department of Psychology
Cambridge, MA 02139

Dr. H. Wallace Sinaiko
Smithsonian Institution
Manpower R&D Program
801 N. Pitt Street, Suite 120
Alexandria, VA 22314-1713

Dr. H. P. Van Cott
NAS-National Research Council (COHF)
2101 Constitution Avenue, N.W.
Washington, DC 20418

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